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Top quark mass measurements at CDF

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Abstract.
The top quark mass is interesting both as a fundamental parameter of the standard model as well as an important input to precision electroweak tests. The CDF Collaboration has measured the top quark mass with high precision in all decay channels with complementary methods. A combination of the results from CDF gives a top quark mass of $170.5 \pm 1.3(\text{stat.}) \pm 1.8(\text{syst.})$ GeV/c^2.

1. Introduction

The top quark was discovered by the CDF and DØ Collaborations in 1995. Its mass is a fundamental parameter of the standard model of particle physics. In addition, because of the extremely high mass of the top quark, top quark loops introduce large radiative corrections to other observables such as the W-boson mass, and the magnitude of those corrections depends strongly on the top quark mass. In particular, precise measurements of the top quark and W-boson masses are needed to constrain the mass of the elusive Higgs boson, and for consistency studies if the Higgs is observed. The Yukawa coupling of the top quark to a standard model Higgs is rougly one, which may indicate that the top quark has a special role in electroweak symmetry breaking.

At Tevatron energies, the top quarks are mainly pair produced via strong interaction. Each top quark decays before hadronization to a W-boson and a b-quark. The two resulting W bosons decay either hadronically or leptonically, defining the three channels of $t\bar{t}$ events: dilepton for two leptonic decays, lepton+jets for one leptonic and one hadronic decay, and all-hadronic for two hadronic decays.

Reconstruction of the top quark's mass presents several experimental challenges. The neutrinos from leptonically decaying W-bosons escape the detector, and only the transverse component of the missing energy can be detected. The quarks hadronize and form jets of particles whose energy must be corrected back to the parton-level. The assignment of jets to partons usually have many possible permutations. Finally, there are background processes which mimic $t\bar{t}$ events.

2. Overview of measurement techniques and systematic uncertainties

The mass extraction techniques can be divided into two categories: template methods and matrix element methods. The template methods evaluate one per-event observable which is correlated with the true top quark mass. Typically, a reconstructed top quark mass is taken. Monte Carlo samples with full detector simulation are used to create "templates" of the distribution of this

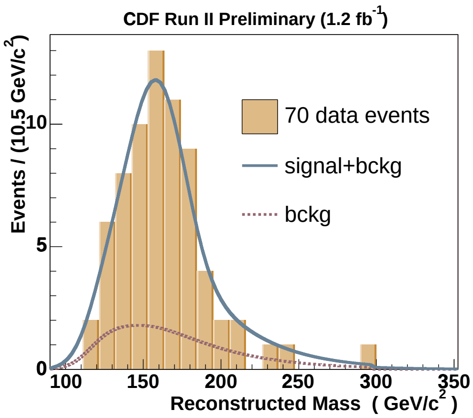

Figure 1. Reconstructed top mass distribution from dilepton events.

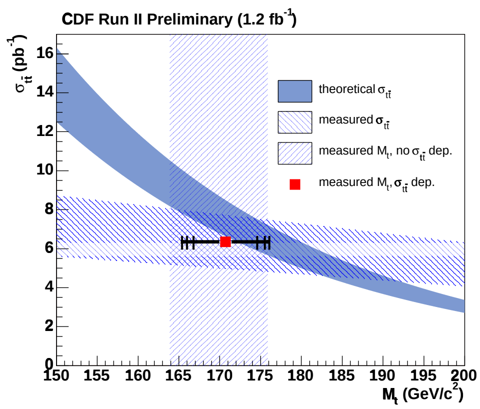

Figure 2. Measured cross section constrained top mass shown in the M_t – $\sigma_{t\bar{t}}$ plane.

variable for signal samples generated with various top masses, and for background processes. A likelihood fit of the data distribution to parametrized templates yields a measurement of the top mass.

Matrix element methods calculate a probability likelihood that a particular event is observed given a true top quark mass. The likelihood is calculated from parton distribution functions, matrix elements for signal and dominant background processes, and "transfer functions" which connect quarks at the matrix element level to observed jets, taking into account fracmentation effects and detector resolutions. The per-event probabilities are multiplied, and the maximum of the resulting curve is taken as a measurement of the top quark mass. Since various simplifying approximations must be made in the interest of computational tractability, the method needs to be calibrated using fully simulated Monte Carlo samples with known value of the generated top mass.

In the lepton+jets and all-hadronic channels, the uncertainty from jet energy scale (JES) can be reduced by using in-situ JES calibration where the invariant dijet mass of the hadronically decaying W-boson is calibrated to the known mass of the W-boson. This converts the dominant systematic uncertainty into a statistical uncertainty, which will improve with more data. All the analyses estimate systematic uncertainties from initial and final state radiation modeling, parton distribution functions, choice of a Monte Carlo generator, and background fraction and shape. In addition, each analysis consider analysis dependent systematic uncertainties.

3. Measurements in dilepton channel

The signature of the dilepton events is two high p_T leptons, missing transerse energy as an indication of the neutrinos escaping the detector, and at least two jets. This channel has low background and only two possible ways to assign a jet to a parton. It is challenging because of low branching ratio, and the event kinematics are underconstrained for top mass fitting.

The top mass reconstruction can be accomplished by assuming a kinematic variable which is not observable on an event-by-event basis, but the distribution of which is predictable and independent of the top mass value. In the template measurement, the distribution of longitudinal momentum of the $t\bar{t}$ system was selected as the top mass independent distribution, and it was scanned over in the mass determination. The sample was divided into two categories determined whether there is at least one or zero b-tagged jets in the event. Since the subsamples have different signal purities, treating them separately increases the power of the likelihood fit. The

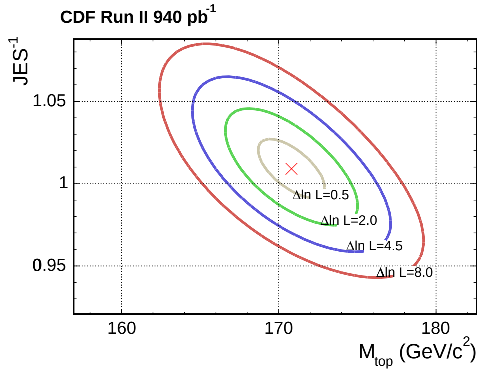

Figure 3. Likelihood countours extracted using matrix element method in lepton+jets channel.

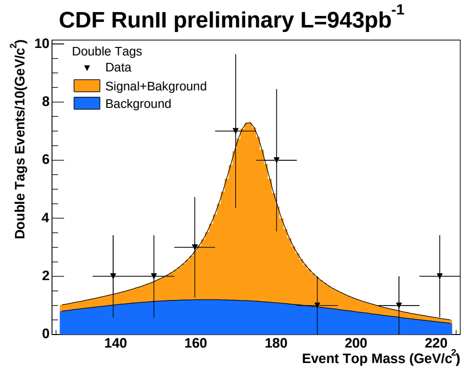

Figure 4. Event top mass distribution from data and simulation using double b-tagged all-hadronic events.

reconstructed top mass distribution from 70 data events is shown in Fig. 1, from which the measured top mass is $169.7^{+5.2}_{-4.9}(\text{stat.}) \pm 3.1(\text{syst.})$ GeV$/c^2$ [1]. This measurement was improved further by including a cross section constraint: the top mass information is extracted from reconstructed top mass distribution as well as from observed number of events. We measure $170.7^{+4.2}_{-3.9}(\text{stat.}) \pm 2.6(\text{syst.}) \pm 2.4(\text{theory})$ GeV$/c^2$ [2]. Figure 2 shows the good agreement between the two measurements.

The matrix element method in the dilepton channel calculates the event probability density for the signal and three major background processes. All unmeasured quantities and major experimental resolutions are integrated over. From a sample of 78 events, corresponding to 1.0 fb^{-1}, we measure a top quark mass of $164.5 \pm 3.9(\text{stat.}) \pm 3.9(\text{syst.})$ GeV$/c^2$ [3].

4. Measurements in lepton+jets channel

The lepton+jets channel has traditionally provided the most precise measurements of the top quark mass. This channel provides a good compromise of a reasonable branching fraction and a reasonable signal-to-background ratio, and the uncertainty from the jet energy scale can be reduced using in-situ calibration from hadronically decaying W-boson. These events are selected by requiring one lepton, missing transerse energy, and at least four jets.

The single most precise top mass measurement shown in the conference was achieved using a matrix element method in this channel. A likelihood was created for each event by combining a signal probability with a background probability. This likelihood was maximized for the top quark mass, JES, and the fraction of events consistent with the signal hypothesis. Since the leading-order matrix element was used, events with extra radiation are not well described. Therefore the sample was restricted to events with exactly four reconstructed jets. From a sample of 166 events corresponding to 0.94 fb^{-1}, the extracted top quark mass is $170.9 \pm 2.2(\text{stat.} + \text{JES}) \pm 1.4(\text{syst.})$ GeV$/c^2$ [4]. The likelihood contours extracted using this analysis are shown in Fig. 3.

The two-dimensional template method in this channel divides the sample into four subsamples according to different b-tag requirements and jet E_T selection. For each subsample, templates for top mass and JES are formed using the reconstructed top mass and the invariant W dijet mass, which are then compared to data using likelihood fit. There is an additional χ^2 cut to ensure that only well reconstructed events are considered. We measure a top quark mass of $173.4 \pm 2.5(\text{stat.} + \text{JES}) \pm 1.3(\text{syst.})$ GeV$/c^2$ [5] using 360 selected events from a data sample corresponding to 0.68 fb^{-1}.

5. Measurements in all-hadronic channel

The signature of the all-hadronic events is at least six jets. The all-hadronic channel has the advantage of high branching ratio, and the complete reconstruction of the top quarks because there are no neutrinos in the final state. The channel is challenging due to a huge background contamination and large combinatorial jet-parton ambiquity. If no jet flavor is required, there are 90 possible ways to assign a jet to a parton.

The latest mass measurement in this channel is a combination of a template and matrix element methods. The likelihood from matrix element is calculated for each event. First the likelihood is used to select the candidate events, then the top mass which maximizes the probability is taken as a per-event reconstructed top mass. In addition to top mass templates, dijet mass templates are created to execute the in-situ jet energy scale calibration, and the sample is divided into single and double b-tagged subsamples to improve sensitivity. Figure 4 demonstrates the good signal-to-background fraction achieved for double b-tagged events. From a data sample of 72 events, which corresponds to 0.9 fb^{-1}, the measured top quark mass is $171.1 \pm 3.7(\text{stat.} + \text{JES}) \pm 2.1(\text{syst.})$ GeV/c^2 [6].

The one-dimensional template analysis utilizes kinematic fitter to calculate per-event reconstructed top mass. All the possible jet to parton combinations are considered, and the one with smallest χ^2 is selected. From a data sample corresponding to 1.0 fb^{-1}, 772 events pass the neural network based selection criteria and yield a top quark mass of $174.0 \pm 2.2(\text{stat.}) \pm 4.8(\text{syst.})$ GeV/c^2 [7]. The systematic uncertainty is dominated by uncertainty from jet energy scale, 4.5 GeV/c^2.

6. Combination

The most precise measurements from each channel were combined with Run I measurements using Best Linear Unbiased Estimator [8] which accounts for correlations between measurements. This yields a CDF combined top quark mass of $170.5 \pm 1.3(\text{stat.}) \pm 1.8(\text{syst.})$ GeV/c^2. The CDF and DØ combination results in a top quark mass of $170.9 \pm 1.1(\text{stat.}) \pm 1.5(\text{syst.})$ GeV/c^2.

7. Conclusions

CDF has a robust program of top quark mass measurements using complementary techniques. We have excellent results from all the decay channels. The combination of these measurements with measurements from DØ results in a top quark mass of $170.9 \pm 1.1(\text{stat.}) \pm 1.5(\text{syst.})$ GeV/c^2. Together with the W-boson mass measurement, it limits the mass of the standard model Higgs to be smaller than 144 GeV/c^2 with 95% CL [9].

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